GROUND SHOCK FROM PENETRATING CONVENTIONAL WEAPONS

James L. Drake and Charles D. Little, Jr.

U. S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

ABSTRACT

This paper presents results of an analysis of ground shock data from more than one hundred explosion tests conducted in soil over the past 35 years. Burst positions varied from fully buried to contact detonations in soil and for shallow depths into concrete protective overlays. Soil conditions ranged from loose dry sand to saturated clay. Empirical equations are presented that predict the magnitude and time histories of the expected stresses and ground motions as a function of burst position, soil indices and burster layer thickness.

BACKGROUND

More than one hundred explosion tests have been performed over the past 35 years in soil to characterize the ground shock produced by buried conventional munitions. Lampson (1) conducted pioneering tests during World War II with buried charges in several soil types from which cube root scaling was developed and verified. Following Lampson's lead, the MOLE and UET tests (2,3) were conducted in the early 1950's to extend the ground shock data base to other soils and rocks. Since that time many other buried burst tests have been conducted in a wide variety of soils with charges from 1 pound to 500 tons (4-11). Many other small-scale tests have gone unreported.

Tests performed for special projects produced the first measurements of stresses directly beneath near-surface explosions on burster slabs (12,13). Coupling of shallow explosions from penetrating weapons was investigated by Ingram (8) in the CENSE program and by Drake and Little (unreported). Brown, et al (14), investigated the propagation of ground shock through rock rubble overlays. All totaled, more than 50 tests have been conducted just to determine explosive coupling from partially buried weapons in burster slabs.

Ground shock data from these tests were drawn together and analyzed to provide an update to the Army design manual, TM 5-855-1, "Fundamentals of Protective Design for Conventional Weapons." The result of that analysis is the basis for this paper. Due to the limited space provided, only the empirical prediction equations are given.

GROUND SHOCK THREAT

The ground shock produced by bombs exploding on or within the ground near buried structures generally provides the dominant threat to these facilities. Stresses from buried bursts can be greater in magnitude and much longer duration than corresponding bursts in air.

Significant enhancement of the stresses and ground motions will occur as the weapon penetrates more deeply into the surrounding soil or backfill before it denotates. Often, protective layers of concrete or rock rubble are provided over the structure to limit the weapon penetration thus reducing the effective coupling of the explosion and increasing the weapon standoff.

Important variables affecting the intensity of the loading are: a) weapon size and distance to the structure, b) the mechanical properties of the soil or rock, and c) the depth of penetration of the weapon. Of these factors, the effect of soil or rock properties is least predictable by simple handbook methods. Ground shock intensity may vary by more than two orders of magnitude when the soil is varied from low density dry soils to saturated clays.

There are two important cases to consider in assessing the ground shock threat to buried facilities: 1) bombs that explode overhead, generally on or within the protective concrete or rock rubble overlay, causing a direct loading of the roof slab, and 2) weapons that penetrate into the surrounding soil and detonate beside the facility loading the walls and floor. While the same general ground shock prediction equations apply for both cases, the role of the site geology and the protective overlay requires a somewhat different application of these equations. These cases are shown in Figure 1.

SOIL PROPERTY EFFECTS

Ground shock propagation in earth media is a complex function of the dynamic constitutive properties of the soil, the explosive products and the geometry of the explosion. No single soil index or combination of indices can adequately describe this process in a simple way for all cases.

Water can have a profound influence on ground shock propagation in cohesive soils, particularly

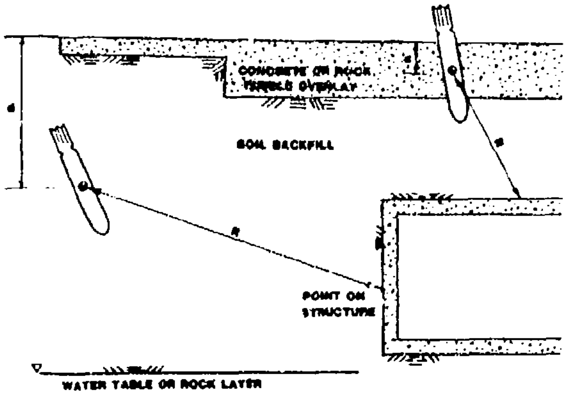

Figure 1. Geometry for explosion against a buried facility

as saturation reaches 95 percent or greater. Typically water is fully bound with the skeletal structures for these soils, providing significant contribution to the overall stiffness and strength of the soil structure. As saturation approachs 100 percent, pronounced increases in peak stresses and accelerations have been observed in wet clays, clay shales and sandy clays. Stresses similar to shock waves in free water have been noted in saturated clays. Saturation as measured by free standing water in boreholes may not be an accurate measure of the true saturation depth, particularly where seasonal water table fluctuations introduce small amounts of air into the soil. Seismic surveys generally will show a sharp jump in the wave speed to more than 5000 feet per second at this depth.

Granular soils with high relative density are generally not strongly influenced by water saturation as are cohesive soils. The stiffness of granular soil is provided by the grain to grain contacts in the skeleton with only a small contribution by the free water. Consequently, controlled laboratory and field experiments in dense nearly saturated sands did not show large influence of the pore water on the resulting shock wave propagation. However, the effects of water in low relative density sands can produce similar effects as those seen in cohesive soils [15]. In these cases, the soil skeleton can collapse, and the grain to grain contact lost resulting in high pore pressures as the sand liquifies. These sites would not normally be considered for construction of hardened facilities.

Seismic velocity, c , is often used as a crude index of soil or rock properties for ground shock prediction purposes. It provides a simple measure of the stiffness and the density of the soil thru the relationship

$$c = \sqrt{\frac{M}{\rho}}$$

where M is the stiffness or modulus of the soil and ρ is its mass density. The seismic velocity also provides a relationship between distance and time.

A great deal of caution must be used in generalizing the use of seismic velocity as a ground shock index. Cementation in granular soils such as dry desert alluvium may result in abnormally high propagation velocities (approaching 4000 feet per second). Yet these materials may exhibit very high air filled voids and low relative densities--qualities that would classify them as very poor transmitters of ground shock. Low seismic velocities, on the other hand, would generally indicate poor ground shock transmission qualities.

The attenuation rate with range of the ground shock magnitude is controlled by the irreversible crushing of the void volume within the soil matrix by the passage of the stress wave. In cohesive soils, the volume of the air filled voids is an index for attenuation of ground motions, while the best index for attenuation rates in granular media is the relative density. Because relative density is not always available, dry unit weight can be an effective index for ground shock attenuation. Soils with high relative density (high dry density) or low air voids will attenuate the ground shock more slowly than low relative density or high air void materials. Figure 2 shows the peak stress from explosions in typical soils.

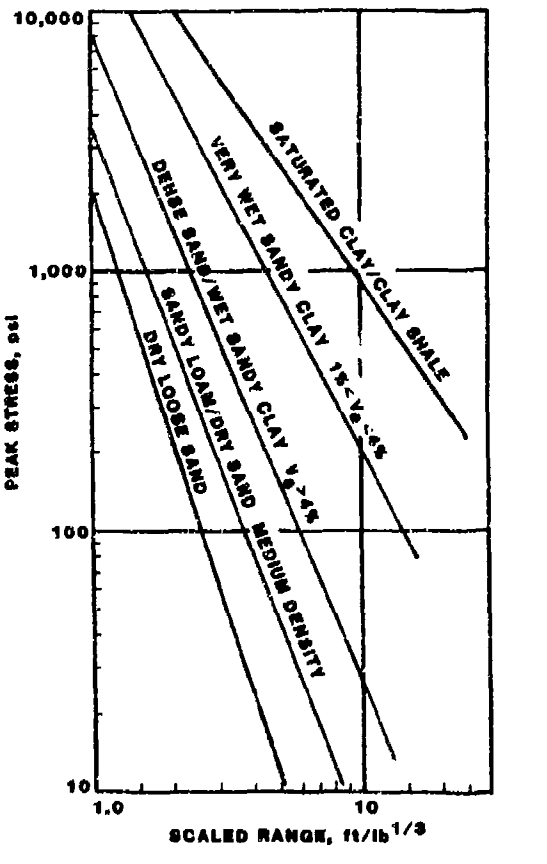

Figure 2. Peak stress from explosions in varying soil types

GROUND SHOCK PREDICTIONS

Stress and particle velocity pulses can be characterized by exponential like time histories that decay rapidly in amplitude and broaden as they propagate outward from the explosion. The characteristic time for these time histories can be measured in arrival time from the source, t_a, where

$$t_a = \frac{R}{c} \tag{1}$$

R is the distance from the explosion and c is the seismic or propagation velocity. Typically these wave forms rise sharply to the peak with the rise time, t_r

$$t_r = 0.1\, t_a \tag{2}$$

this is about 1/10 of the travel time to the target point. From the peak, the pulse decays monotonically with time to nearly zero in 1 to 3 travel times given by the following equations

$$P(t) = P_o e^{-\alpha t/t_a} \qquad t \geq 0 \tag{3a}$$

$$V(t) = V_o(1 - \beta t/t_a)e^{-\beta t/t_a} \qquad t \geq 0 \tag{3b}$$

where P(t) is the stress, V is the particle velocity, and α and β are time constants. While the time constants generally vary with specific site conditions, they can be taken as

$$\alpha = 1.0 \qquad \beta = \frac{1}{2.5}$$

for most applications. P_o and V_o are values of the peak stress and particle velocity to be determined by the following equations. Other waveform parameters such as impulse, displacement and accelerations may be derived from these functions.

Since the characteristic time is inversely proportional to seismic velocity, explosions in high velocity media such as saturated clay will produce very short, high frequency pulses with high accelerations and low displacements. On the other hand, detonations in dry loose materials will cause much longer duration, low frequency ground motions.

Peak particle velocity and peak stress are related by

$$P_o = \rho c\, V_o \tag{4}$$

where ρ is the mass density. Free-field stresses and ground motions from bombs detonating on and within burster layers or in the soil along side the structure are given in the following expressions:

$$P_o = f \cdot (\rho c) \cdot 160 \cdot \left(\frac{R}{W^{1/3}}\right)^{-n} \tag{5a}$$

$$V_o = f \cdot 160 \cdot \left(\frac{R}{W^{1/3}}\right)^{-n}. \tag{5b}$$

$$a_o \cdot W^{1/3} = f \cdot 50 \cdot c \cdot \left(\frac{R}{W^{1/3}}\right)^{-n-1} \tag{5c}$$

$$\frac{d_o}{W^{1/3}} = f \cdot 500\, \frac{1}{c} \left(\frac{R}{W^{1/3}}\right)^{-n+1} \tag{5d}$$

$$\frac{I_o}{W^{1/3}} = f \cdot \rho \cdot 1.1 \cdot \left(\frac{R}{W^{1/3}}\right)^{-n+1} \tag{5e}$$

where P_o is the peak pressure (psi), V_o is the peak particle velocity (ft/sec), a_o is the peak acceleration (g's), d_o is the peak displacement (ft), I_o is the peak impulse (psi-sec), ρ_o is the mass density (lb-sec/ft^4), c is the seismic velocity (ft/sec), ρc is the acoustic impedance (psi/ft/sec), R is the distance to the explosion (ft), W is the charge weight (lb), and f is the coupling factor for near surface detonations. For preliminary design considerations the following table is suggested for selecting the seismic velocity, acoustic impedance and attenuation coefficients:

SUGGESTED COEFFICIENTS FOR DESIGN

Material Description	Seismic Velocity c ft/sec	Acoustic Impedance (ρc) psi/ft/sec	Attenuation Coefficient n
Loose, dry sands and gravels with low relative density	600	12	3-3.25
Sandy loam, loess, dry sands and backfill	1000	22	2.75
Dense sand, with high relative density	1600	44	2.5
Wet sandy clay with air voids (greater than 4 percent)	1800	44	2.5
Saturated sandy clays and sands with small amount of air voids (less than 1 percent)	5000	48	2.25-2.5
Heavy saturated clays and clay shales	>5000	150-180	1.5

A more detailed description is provided in Table 1 for soils encountered in explosion test programs. Simple soil parameters such as wet and dry unit weights, air filled voids and seismic velocity are shown to assist in relating the explosion

effects parameters to the design soil conditions. Note that the attenuation coefficient and seismic velocity are closely related to dry unit weight for granular soils while air void content is important for cohesive soils.

GROUND SHOCK COUPLING FACTOR

The magnitude of the stress and ground motions will be greatly enhanced as the weapon penetrates more deeply into the soil or the protective burster layer before it detonates. A concept of an equivalent effect coupling factor is introduced to account for this effect on the ground shock parameters and is defined as follows:

> The coupling factor, f, is defined as the ratio of the ground shock magnitude from partially to shallow buried weapon to the ground shock magnitude from a fully buried burst in the same medium.

$$f = \frac{(P,\ V,\ d,\ I,\ a)\ \text{near surface}}{(P,\ V,\ d,\ I,\ a)\ \text{contained}}$$

A single coupling factor is applicable for all ground shock parameters that depends upon the depth of burial of the center of the weapon and the medium being penetrated, i.e., soil, concrete or air. It is important to note that the coupling factor concept used here does not produce an equivalent charge but rather, it is a scale factor to reduce the ground shock computed from a buried burst with the full charge weight to account for the shallow burial.

Coupling factors are different for bursts in air, soil and concrete and depend upon the scaled depth of burst of the weapon. These factors are shown in Figure 3. The coupling factor for air is a constant

$$f = 0.14$$

and is recommended for contact bursts.

In the case where a weapon penetrates into more than one material, i.e., a long bomb that penetrates the concrete slab and is partly buried in soil, the coupling factor is computed as the sum of the coupling factors in each of the materials weighted in proportion to the charge weight contained within each medium.

$$f = \sum f_i\left(\frac{W_i}{W}\right) \qquad (6)$$

where f is the total coupling factor, f_i is the coupling factor for each component material, i.e.,

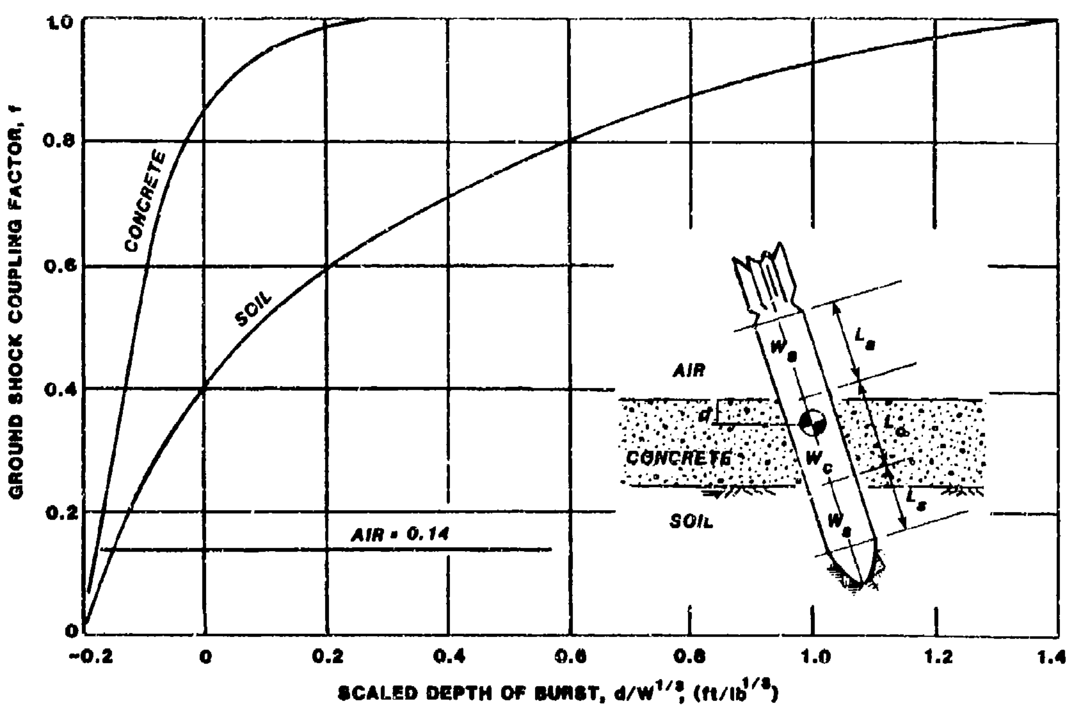

Figure 3. Ground shock coupling factor as a function of scaled depth of burst for air, soil and concrete

air, soil, concrete, W_i is the weight of the charge in contact with each component material, and W is the total charge weight. Since most bombs are cylindrical, the coupling can also be defined as

$$f = \sum f_i\left(\frac{L_i}{L}\right) \tag{7}$$

where L_i is the length of the weapon in contact with each material and L is the total weapon length.

DISCUSSION AND CONCLUSIONS

Empirical expressions were derived from a fit to a large body of ground shock data from buried and near-surface bursts in soil. Several important observations were made concerning the role of soil properties on scaling of ground shock:

1. Near the explosive source, peak particle velocities in soils tend to a single curve that is nearly independent of the soil properties. This observation can be explained in part by the interaction of the detonation wave in the explosive with the soil.

2. Peak stresses scale in proportion to the seismic velocity.

3. Attenuation of the peak ground shock magnitudes is strongly dependent on the relative density in granular soils or to the air void volume in cohesive soils. Because the seismic velocity is also influenced by these parameters, the attenuation coefficient, n , can be estimated from the seismic velocity as

c(fps)	n
500-600	3-3.5
750-1000	3
1000-1400	2.75
1400-1800	2.5
>5000	1.5-2.25

4. Time scales in proportion to the time of arrival. Thus, the pulse tends to spread in proportion to the distance traveled, with a rise time of about 1/10 of the travel time and a duration on the order of 2-3 travel times.

5. Because of the time scaling, peak accelerations are proportional to the seismic velocity, peak displacements are inversely proportional to the seismic velocity while the peak impulse is only sensitive to density variation.

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TABLE 1 SOIL PROPERTIES FROM EXPLOSION TESTS

Soil Description	Dry Unit Weight γ_{dry} lb/ft^3	Total Unit Weight γ lb/ft^3	Air-Filled Voids %	Seismic Velocity c ft/sec	Acoustic Impedance ρc psi/ft/sec	Attenuation Coefficient n
Dry desert alluvium and playa, partially cemented	87	93-100	>25	2100-4200 (1)	40	3-3.25
Loose, dry, poorly graded sand	80	90	>30	600	11.6	3-3.5
Loose wet poorly graded sand-free standing water	97	116	10	500-600	12.5-15	3
Dense dry sand, poorly graded	99	104	32	900-1300	25	2.5-2.75
Dense wet sand, poorly graded-free standing water	108	124	9	1000	22	2.75
Very dense dry sand, relative density ≈100%	105	109	30	1600	44	2.5
Silty-clay, wet	95-100	120-125	9	700-900	18-25	2.75-3
Moist loess, clayey sand	100	122	5-10	1000	28	2.75-3
Wet sandy clay, above water table	95	120-125	4	1800	48	2.5
'Saturated' sand-below water table in marsh	--	--	1-4 (2)	4900	125	2.25-2.5
'Saturated' sandy clay, below water table	78-100	110-124	1-2	5000-6000	130	2-2.5*
'Saturated' sandy clay, below water table	100	125	<1	5000-6600	130-180	1.5
Saturated stiff clay saturated clay-shale	--	120-130	0	>5000	135	1.5

(1) High because of cementation.
(2) Estimated.